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Abstract
In this paper, we verify experimentally the recently proposed theory on suppression of the spatial dispersion in an artificial plasma. We make use of the image principle and assume effectively local material parameters of the artificial plasma, in which the spatial dispersion has been suppressed, and measure the reflection from an impenetrable grounded surface. The plasma resonance can be clearly distinguished from the measurement results at the plasma frequency independently from the incidence angle. The agreement between the measurement results and the theory and simulations is very good.

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Experimental verification of the suppression of spatial dispersion in artificial plasma

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In this paper, we verify experimentally the recently proposed theory on suppression of the spatial dispersion in an artificial plasma. We make use of the image principle and assume effectively local material parameters of the artificial plasma, in which the spatial dispersion has been suppressed, and measure the reflection from an impenetrable grounded surface. The plasma resonance can be clearly distinguished from the measurement results at the plasma frequency independently from the incidence angle. The agreement between the measurement results and the theory and simulations is very good. © *2010 American Institute of Physics*. [doi:10.1063/1.3327828]

The possibility to achieve effectively near-zero or even negative values for the effective permittivity $\varepsilon_{\mathrm{eff}}$ has recently attracted a lot of attention in the literature. One of the reasons behind the great interest toward these artificial materials is surely the proposed applications that are based on these exotic values of permittivity. For instance, the effectively near-zero values of permittivity are needed in very promising cloaking[1–4] and antenna pattern shaping techniques.[5,6] Further, the negative effective permittivity is needed for the realization of left-handed media and superlensing.[7–9] The effectively zero-permittivity or negative values for the effective permittivity needed for such applications can be found in plasma. The electric properties of plasma can be mimicked in waveguiding applications with a parallel-plate guide or with a rectangular waveguide.[10] Indeed, such guides have been used recently to demonstrate the squeezing and tunneling of energy through an ultranarrow waveguide channel.[11] Further, in other than waveguide applications such exotic values for the effective permittivity can be found in artificial plasma composed of wire medium.[10] Wire medium is composed of long parallel wires separated from one another with a certain lattice constant. Depending on the application and the exciting electric field, the wires can be directed into one-, two- or three directions. For brevity, we will concentrate in this paper only on the case where the wires are directed only along one direction.

Wire medium is reasonably well-known in the microwave frequencies since the 1950s and the works of Brown[12] and Rotman.[10] In Refs. 10 and 12 the incident wave was considered to have a parallel polarization with straight wires in a two-dimensional (2D) lattice and the medium was characterized with a local model for the effective permittivity as follows:

$$\varepsilon_{\mathrm{eff}} = \varepsilon\left(1 - \frac{k_{\mathrm{p}}^2}{k^2}\right), \tag{1}$$

where k_{p} is the plasma wave number connected with the plasma frequency f_{p} and $k = k_0\sqrt{\varepsilon}$ is the wave number in the surrounding medium. In this case the zero-permittivity values are obtained at the plasma frequency and the negative values below the plasma frequency. However, for cases where the electric field is no longer parallel to the wires, but has some phase difference along the wires, the wire medium is known to exhibit spatial dispersion.[13] In a spatially dispersive material the properties of the material are dependent on the direction of the wave vector in the material. In these cases the medium can be characterized with a nonlocal model for the effective permittivity as follows:[13]

$$\varepsilon_{\mathrm{eff}} = \varepsilon\left(1 - \frac{k_{\mathrm{p}}^2}{k^2 - q_{\mathrm{z}}^2}\right), \tag{2}$$

where q_{z} is the component of the wave vector $\mathbf{q} = (q_{\mathrm{x}}, q_{\mathrm{y}}, q_{\mathrm{z}})$ along the wires. The plasma wave number can be calculated for a square lattice using the following approximation given by Belov *et al.*.[13]

$$k_{\mathrm{p}}^2 = \frac{2\pi}{a^2\left[\ln\left(\dfrac{a}{2\pi r_0}\right) + 0.5275\right]}, \tag{3}$$

where a is the lattice constant and r_0 is the radius of the wires. In the case of extreme anisotropy, where the waves propagates in the wire medium parallel to the wires, wire medium has found applications in sub-wavelength imaging.[14–16]

Due to the effects of spatial dispersion in the wire medium in applications such as electromagnetic cloaking or superlensing, where the operation is optimized for a certain value of effective permittivity, the operation is limited to a certain plane of incidence and polarization. Recently, the possibility to suppress the spatial dispersion in the wire medium has been studied in Refs. 17–19. In Ref. 17 it was

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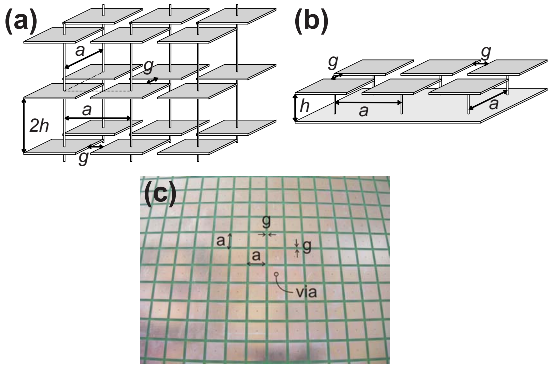

FIG. 1. (Color online) (a) A 1D wire medium structure in which metallic plates have been inserted to suppress the spatial dispersion. Because of this, the effective permittivity is assumed to arise from the local electromagnetic fields and the response from a layer of the wire medium structure should be the same as from a larger structure comprising multiple layers. (b) The structure of a slab of wire medium can be further simplified by using the image principle and a ground plane. (c) Photograph of the measured sample in which the metallic wires are replaced by hollow vias connecting the metallic patches to the ground plane.

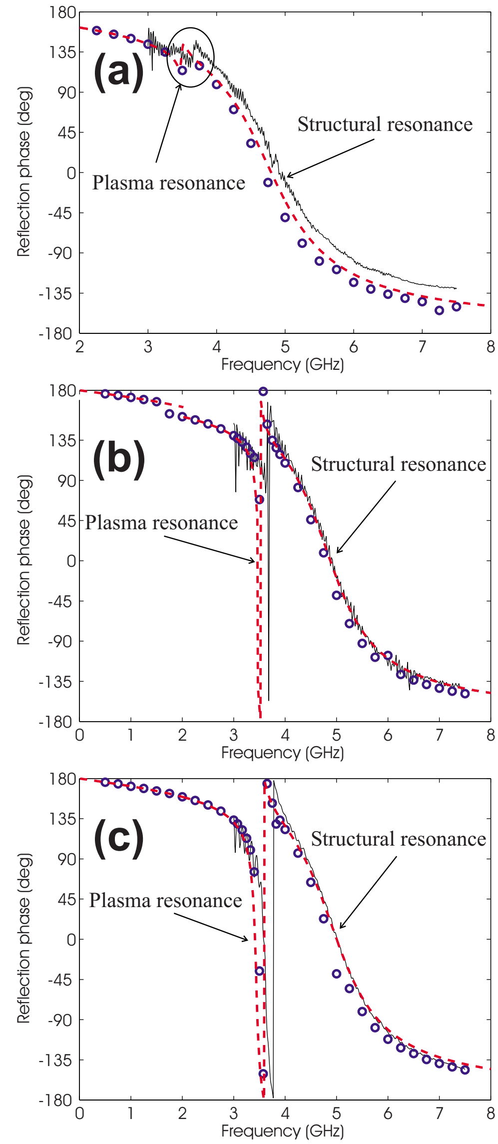

FIG. 2. (Color online) The reflection phase diagrams for the incidence angle of (a) 10°, (b) 20°, and (c) 30°. The measurement results are plotted with solid black line, the analytical results are plotted with dashed red line, and the simulation results are plotted with blue circles.

suggested that one possible way to suppress the spatial dispersion in the wire medium was to increase the capacitance between the adjacent wires with larger metallic patches. The results were verified only numerically. This is a very similar way as in Ref. 18, where it was shown both analytically and numerically that by choosing the height and the lattice constant of the wire medium slab properly, the spatial dispersion in the wire medium in the context of artificial impedance surfaces is suppressed. The effects of the spatial dispersion occur due to the accumulation of charges on the wires. By inserting metallic plates to the wire medium relatively close from each other, one prevents the charges from accumulating on the wires and preserves the relatively uniform current distribution associated with spatially nondispersive materials. For the discussed applications the suppression of the spatial dispersion in the wire medium would result as more feasible designs and enlargement of the operational range. The objective of this paper is to verify experimentally the theory of suppression of the spatial dispersion in the wire medium and the results of Ref. 18.

In Fig. 1(a) a one dimensional (1D) wire medium structure with lattice constant a and wire radius r_0 is illustrated. Here, metallic patches have been inserted equidistantly into the structure with separation $2h$ from one another along the wires and with separation g from the adjacent patches in the $(x-y)$ plane. For less polarization dependent or less anisotropic structure wire lattices aligned also in the two remaining orthogonal directions can be added, in the similar manner as in Fig. 1(a). The structure in Fig. 1(a) can be reduced to a surface that comprises just one layer of the structure between a pair of metallic patches. For manufacturing purposes, the structure can be further simplified by using the image principle and a ground plane, as illustrated in Fig. 1(b). The resulting structure resembles the mushroom-type artificial impedance surfaces first proposed in Ref. 20. Such structures have been studied thoroughly in our recent work,[18] where it was found that at plasma resonance of the wire medium, the surface impedance of the structure becomes very large for the incident Transverse Magnetic (TM) fields excluding normal incidence. This can be explained for a grounded wire medium slab as follows: at the plasmonic resonance of wire medium with uniaxial symmetry the normal component of the effective permittivity approaches zero whereas the transverse component remains fixed. This causes a high wave impedance for the TM fields $Z^{\mathrm{TM}}=\sqrt{\omega^2\varepsilon_t\mu_t-k_t^2\varepsilon_t/\varepsilon_n}$ and also the waves traveling along the normal axis in the wire medium become evanescent. The wire medium has no effect on the incident Transverse Electric (TE) fields.

Since the grounded wire medium slab is impenetrable, the high surface impedance for the incident TM fields is observed from a 0° reflection phase at the surface. For a spatially nondispersive wire medium change in the angle of incidence should not affect the performance of the surface, that is the plasmonic resonance should occur at the same frequency independent from the incidence angle. To verify our theory we have conducted reflection phase measurements for a structure such as the one depicted in Fig. 1(b). See Fig. 1(c) for a photograph of the measured sample. The reflection phase measurements were carried out in an anechoic chamber with two ETS-EMCO Model 3164–03 horn antennas, a HP8722C network analyzer, and a 30×30 cm^2 sample with design parameters $a=10$ mm, $g=1.25$ mm, $h=3$ mm, $r_0=0.2$ mm, and $\varepsilon_r=4.5(1-j0.02)$. The sample was positioned on a rotation unit that has the accuracy of $\pm0.03°$. The position of the transmitting and receiving antenna was aligned with a laser and two mirrors.

The reflection coefficient of the sample was extracted from the measurements by making two measurements, one for the sample and one for a solid metal plate of the same size, and by using the physical optics approximation. According to the physical optics approximation the currents induced to these surfaces by the incident field should differ only by the factor corresponding to their reflection coefficients. Therefore, the reflection coefficient of an infinitely large high-impedance surface is calculated from the measurement results as $R=-A/B$, where A is the reflection coefficient of the sample and B is the reflection coefficient of the metal plate.

The reflection phase extracted from the measurement results is compared with the analytical and simulated results. The analytical expressions for the surface impedance of the sample have been derived, e.g., in Ref. 21 assuming local model for the effective permittivity of wire medium and in Ref. 18 when the wire medium is spatially dispersive. The simulations have been done using Ansoft's high frequency structure simulator (HFSS). Because of the presence of the ground plane, we expect to see two resonances in the sample: one at the vicinity of the plasma resonance of the wire medium and another resonance at higher frequencies corresponding to the structural resonance of the surface. At the higher resonance frequency the inductive response from the grounded material slab fulfil the resonance condition with the capacitive response of the metallic patch array at the air interface. This resonance is well predicted by our analytical expressions and simulations and can be easily distinguished from the resonance of interest, i.e., from the plasma resonance of the wire medium. The measurement results for incidence angles of 10°, 20°, and 30° are compared in Figs. 2(a)–2(c), respectively, with the analytical and simulation results. The comparison show that there is an excellent agreement between the different results.

For the proposed wire medium lattice constant and wire radius the normalized plasma frequency is analytically estimated to be approximately at 3.5 GHz. Examination of Figs. 2(a)–2(c) shows that a resonance is seen in each of the reflection phase diagrams at this frequency. Furthermore, both analytical expressions, the one taking the spatial dispersion of the wire medium into account and the one that does not, give almost exactly the same results for the proposed sample, which further highlights the fact that the spatial dispersion is indeed suppressed in the wire medium. For this reason only the analytical results according to the model that assumes local effective permittivity for the wire medium are plotted. We can see also that for larger angles of incidence the electric field component parallel to the vertical wires grows and the plasma resonance effect becomes stronger.

In conclusion, these experimental results verify and support the theory on suppression of the spatial dispersion in artificial plasma. The suppression of the spatial dispersion offers possibilities to increase the range of feasibility for superlensing and plasmonic cloaking.

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